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VELOCITY CHARACTERISTICS ALONG A SMALL STEP–POOL CHANNEL

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ABSTRACT

This paper summarizes measurements of velocity along three reaches of a small mountain channel with step–pool bedforms. A one-dimensional electromagnetic current meter was used to record velocity fluctuations at 37 fixed measurement points during five measurement intervals spanning the peak of the annual snowmelt hydrograph. Measurement cross-sections were located upstream from a bed-step, at the step lip, downstream from the step, and in a uniform-gradient run. Data analyses focused on characteristics of velocity profiles, and on correlations between velocity characteristics and the potential control variables bedform type, reach gradient and flow depth. To test the hypothesis that velocity characteristics are related to channel bedform types, ANOVA and ANCOVA tests were performed for the average velocity and coefficient of variation of point velocity data. Results indicate that high frequency velocity variations correlate to some degree with both channel characteristics and discharge. Velocity became more variable as stage increased, particularly at low-gradient reaches with less variable bed roughness. Velocity profiles suggest that locations immediately downstream from bed-steps are dominated by wake turbulence from mid-profile shear layers. Locations immediately upstream from steps, at step lips, and in runs are dominated by bed-generated turbulence. Adverse pressure gradients upstream and downstream from steps may be enhancing turbulence generation, whereas favourable pressure gradients at steps are suppressing turbulence. The bed-generated turbulence and skin friction of runs appear to be less effective energy dissipators than the wake-generated turbulence and form drag of step–pool bedforms. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: step–pool bedforms; velocity variations; bed-generated turbulence; wake-generated turbulence

INTRODUCTION

Velocity fluctuations as detected using electromagnetic current meters (ECMs) have been interpreted by numerous investigators as indicators of flow turbulence in natural channels. These investigators have focused on gravel-bed channels with pool–riffle sequences (e.g. Clifford, 1993a; Clifford and French, 1993; Robert, 1997). The most common approach has been to examine velocity time-series for systematic differences in structure that would reveal the frequency of vortex shedding (Aubrey and Trowbridge, 1985; Best, 1993; Kirkbride, 1993; Lane *et al.*, 1993; Robert *et al.*, 1993). This work has shown varying scales of turbulence and flow structure associated with varying bedforms (Clifford, 1993b; Clifford and French, 1993; Nelson *et al.*, 1993, 1995; Robert, 1997) and bed roughness (Robert *et al.*, 1992, 1993; Clifford, 1996). An understanding of such variability is important to understanding bedload transport and bedform maintenance because of feedbacks between turbulence and the channel bed (DeSerres *et al.*, 1999). For example, Clifford (1993a) demonstrated that spatial differences in the near-bed turbulence field caused by bed topography create differences in the entrainment of bed sediments, which then alter bed topography. However, similar studies have not been conducted for boulder-bed step–pool channels, where the velocity fluctuations may vary more dramatically between steps and pools. This paper summarizes a simple characterization of velocity fluctuations along a small mountain channel with step–pool bedforms.

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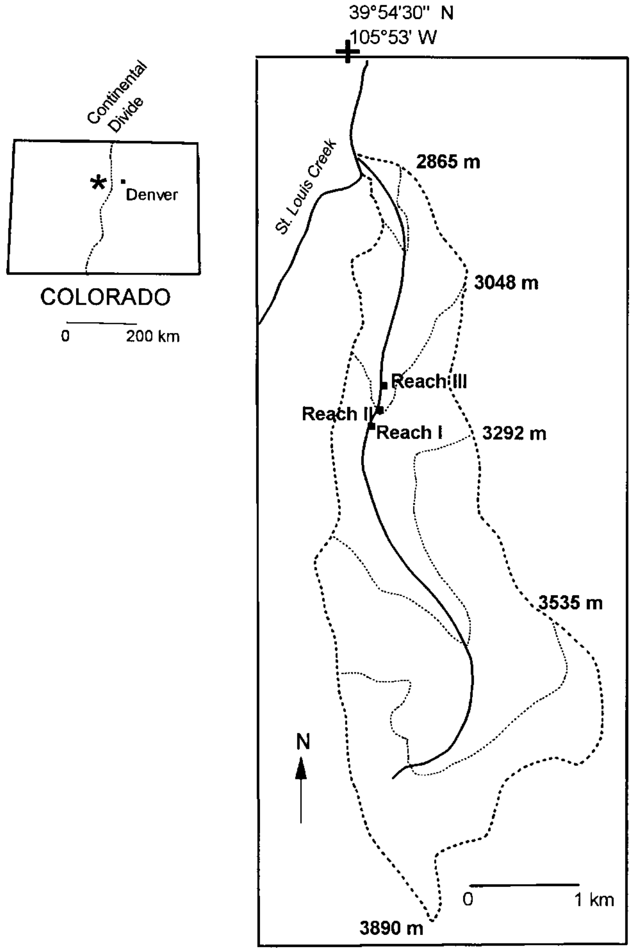

Figure 1. Location map of East St Louis Creek and three study reaches

The characterization reported here is simple because we used fairly simple instrumentation (a single, one-dimensional ECM) to record velocity fluctuations at 37 fixed measurement points during five measurement intervals designed to include the rising limb, peak and falling limb of the annual snowmelt hydrograph. We also measured a thalweg velocity profile for each cross-section during three measurement intervals spanning the snowmelt hydrograph. By choosing measurement points upstream from bed-steps, at the step lip, in the pools below steps, and in the uniform runs between steps, we were able to examine whether velocity characteristics vary consistently with bedform type. We were also able to draw inferences from the velocity data about turbulence generation over various bedforms at differing discharges.

We began with the assumption that turbulence is reflected by higher frequency velocity fluctuations as detectable using a one-dimensional ECM set at 2 s fixed point averaging. Although many field investigations (e.g. Lapointe *et al.*, 1996; Clifford, 1997) examine higher frequency velocity variations than investigated in this study, we hypothesized that velocity fluctuations averaged over 2 s intervals can yield general information about the location and mechanisms for turbulence generation in step–pool environments. We then used simple, univariate statistical techniques to test for significant correlations among variables. Our primary objective was to provide some insight into the complicated hydraulics of step–pool channels.

Table I. Characteristics of the three study reaches along East St Louis Creek

Reach	Channel gradient over 25m (m/m)	Cross-section number	Bankfull channel width (m)	D_{50} (mm)	D_{84} (mm)	D_{84}/D_{50}	Channel gradient over 0·5 m (m/m)	Bedform type
I	0·0625	1	3·1	36	130	3·6	−0·012	At step
		2	2·2	12	80	6·7	0·04	Upstream from step
		3	2·2	32	98	3·1	0·215	Downstream from step
II	0·0254	7	3·4	18	52	2·9	0·02	Run
		8	3·4	11	48	4·4	0·02	Run
III	0·1232	9	2·6	26	95	3·7	0·074	At step
		10	3·2	18	56	3·1	0·15	Upstream from step
		11	3·5	21	90	4·3	0·312	Downstream from step

FIELD AREA

East St Louis Creek drains 8 km^2 within the Fraser Experimental Forest, approximately 80 km west of Denver, Colorado, USA (Figure 1). The creek begins above timberline, at an elevation of 3890 m, and flows north into St Louis Creek at an elevation of 2780 m. St Louis Creek is tributary to the Fraser River, in the upper Colorado River basin.

The basin has a cold temperate climate, and two-thirds of the 740 mm of mean annual precipitation falls as snow (Alexander *et al.*, 1985). A total of 95 per cent of the stream runoff is derived from snowmelt, with the remaining 5 per cent from summer rainfall (Heede, 1972; Alexander *et al.*, 1985). The US Forest Service has maintained a gauging station near the mouth of the creek since 1943. Approximately 80 per cent of the total annual flow occurs from April to October (Heede, 1972), with peak discharge in mid-June (Troendle, 1992). Base flow at the gauge is 0·028 m^3 s^{-1} and mean annual peak flow is 0·58 m^3 s^{-1}. Peak discharge at the gauge during the June–September 1995 study period was 0·68 m^3 s^{-1} on 18 June.

Three study reaches, at elevations of 3015–3050 m, were chosen along East St Louis Creek (Figure 1). The creek has large downstream variations in reach-scale (one to ten channel widths) channel gradient (Table I). Average valley slope within the study area is 9·3 per cent. Valley-bottom widths range from 15 to 75 m, while the channel itself averages 3·0 m. Channel shape is typically rectangular, with channel banks stabilized by riparian vegetation, large boulders and woody debris.

METHODS

Two of the study reaches contained step–pool sequences, and the third was a run. The step–pool reaches each included three measurement cross-sections: 0·5 m upstream from a step, at the step lip, and 0·5 m downstream from the step. The study reach with a run included two measurement cross-sections. At the beginning of the field season, we established a fixed reference line above the bankfull flow depth at each cross-section. Measurement points were chosen at 0·5 m intervals along this line, so that each cross-section included four to six measurement points, depending on cross-section width. Based on flow depth during the first measurement day, we chose a measurement depth at 0·6 of the flow depth at each measurement point. These measurement locations were then kept fixed with respect to elevation above the bed throughout the sampling season. Velocity measurements were based on 2 s fixed point averaging over a timespan of at least 3 min.

Measurements were conducted using a Marsh-McBirney Model 2000 electromagnetic current meter. The Model 2000 has a teardrop-shaped head, low-pass digital filtering, zero stability at $\pm$ 0·015 m s^{-1}, an accuracy of $\pm$ 2 per cent reading plus zero stability, and a frequency of 30 Hz. In order to minimize disruption of flow and of the channel bed, sampling was conducted from a portable bridge consisting of an aluminium ladder resting on sawhorses on the channel banks. Sampling was conducted on 12, 13, 19 and 20 June, and on 12 September 1995. During each sampling day, measurements were collected sequentially from each

(a)

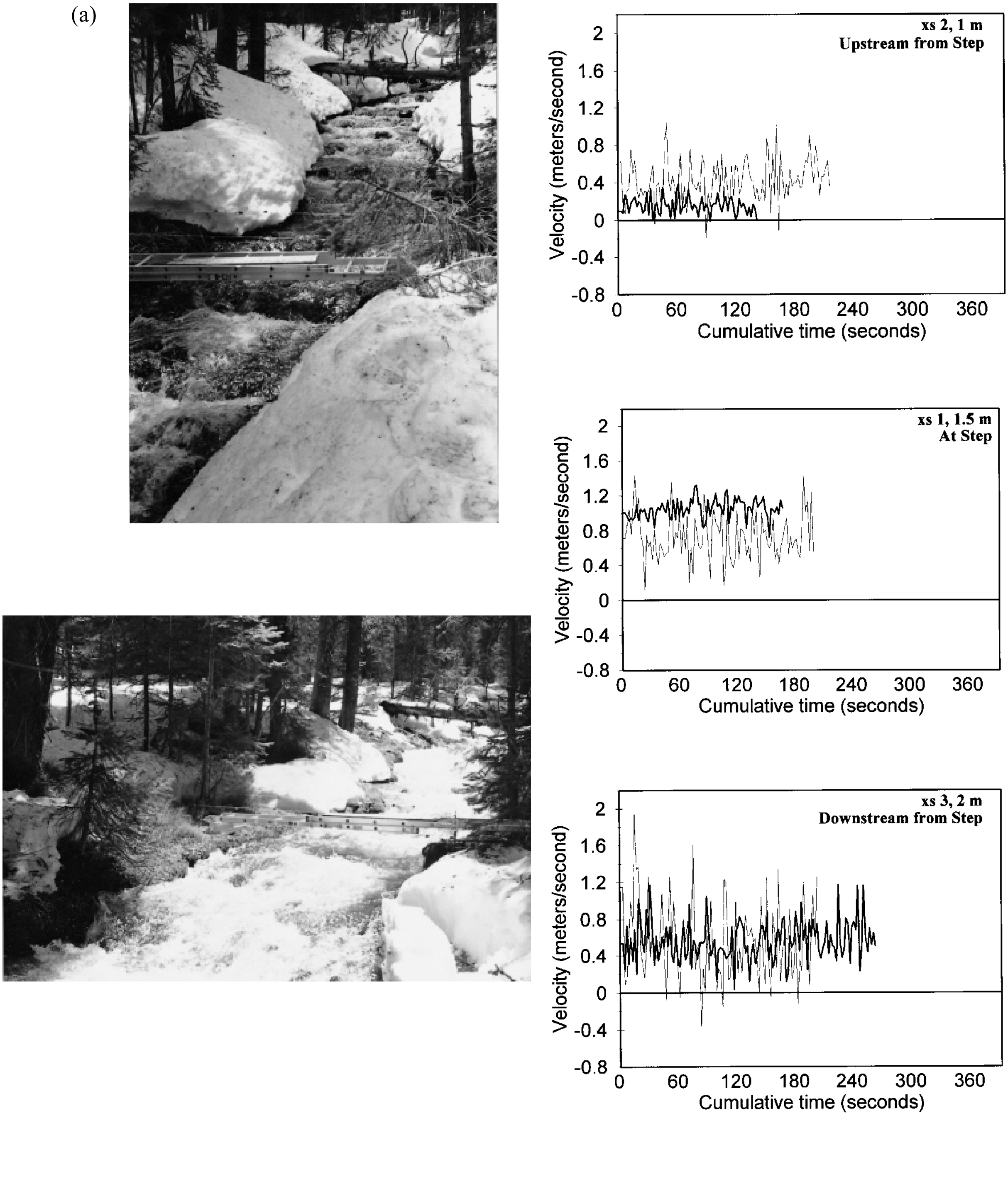

Figure 2. Photographs of each study reach on 12 June and 19 June, and accompanying velocity series at low (heavy line: 12, June 1995) and high (light line; 19, June 1995) discharges. Strings with tabs are at cross-section locations. (a) Reach I; (b) Reach II; (c) Reach III

(b)

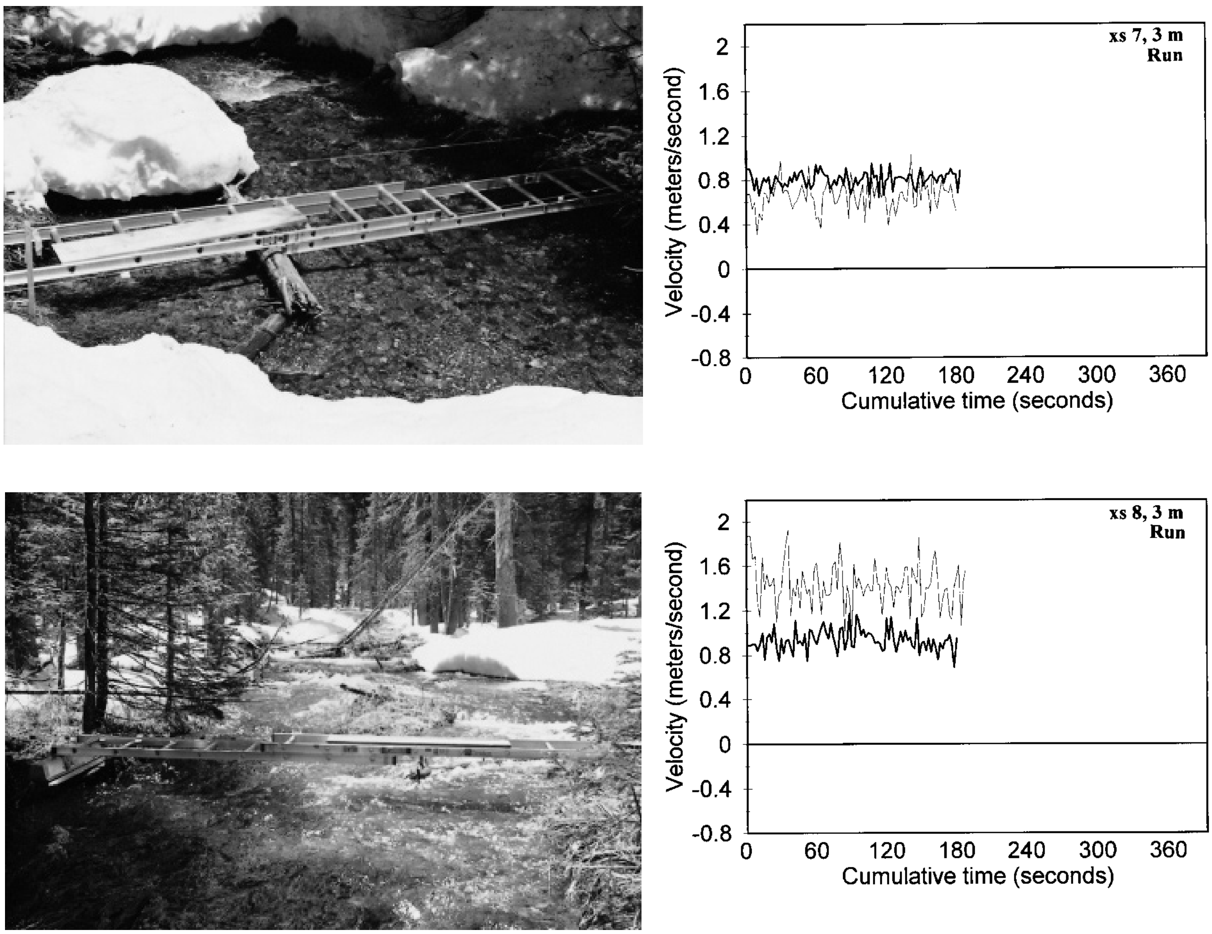

Figure 2. (continued).

measurement point. Staff gauges at each study reach were used to develop a rating curve for calculation of reach discharge at the time of measurement. The peak discharge of 0·62 $m^3 s^{-1}$ occurred on 19 June; the lowest measured discharge of 0·05 $m^3 s^{-1}$ on 12 September.

In addition to the point velocity measurements, we measured velocity profiles at the thalweg of each cross-section on 13, 19 and 20 June 1995. The measurements for each profile were taken sequentially at 2 cm intervals. Each velocity measurement in a profile was based on 6 s fixed point averages taken over a timespan of 1 min.

Visual inspection of velocity profiles indicated differences in velocity characteristics between channel bedform features. To test the hypothesis that velocity characteristics are related to channel bedform type with the larger velocity data set, analyses of variance (ANOVA) and analyses of covariance (ANCOVA) tests were performed for the average velocity and coefficient of variation (CV) point data. Average velocity and coefficient of variation (standard deviation/mean $\times$ 100 per cent) were determined for each measurement location, and tested for normality and unequal variances before conducting the ANOVA and ANCOVA procedures. The coefficient of variation is equivalent to the root mean square (RMS) divided by the mean reported as a percentage (RMS/Mean $\times$ 100 per cent), and is used to standardize the variance for the higher

(c)

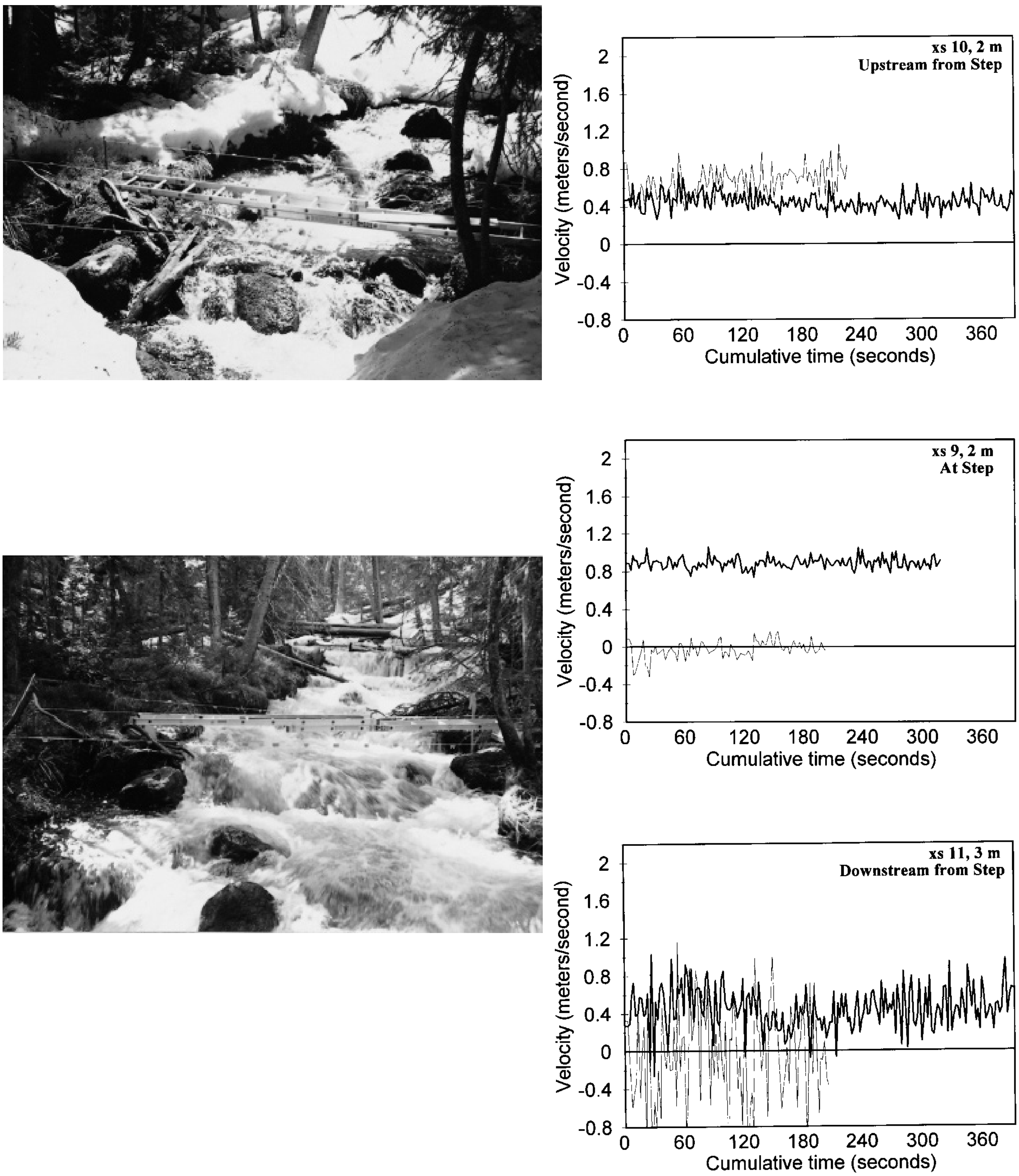

Figure 2 (continued).

Table II. Summary of point-averaged velocity data for each sampling day: mean velocity (in m s^{-1}) and coefficient of variation (CV) are given for each measurement date:

Cross-section, location	12 June		13 June		19 June		20 June		12 September		
	Mean vel.	CV	Mean vel.	CV	Mean vel.	CV	Mean vel.	CV	Mean vel.	CV	Bedform type
XS 1											At step
1·0 m	0·12	33	0·32	28	0·87	34	1·30	24	0·19	32	
1·5 m	1·05	10	0·91	12	0·73	37	1·09	26	0·78	31	
2·0 m	0·55	18	0·14	100	0·86	38	1·27	19	0·22	123	
2·5 m	0·82	8	0·75	12	0·81	22	0·83	36	0·28	14	
XS 2											Upstream from step
1·0 m	0·16	56	0·14	79	0·42	52	0·58	45	0·34	29	
1·5 m	1·00	14	1·00	12	1·78	17	1·97	21	0·75	19	
2·0 m	0·44	11	0·14	79	1·00	38	0·90	32	0·35	14	
2·5 m	0·33	12	0·41	17	0·64	28	0·36	31	0·14	14	
XS 3											Downstream from step
1·5 m	1·31	13	1·41	13	1·95	38	1·29	29	1·40	11	
2·0 m	0·56	39	0·92	32	0·56	75	0·57	58	0·13	38	
2·5 m	0·97	20	1·00	14	1·28	28	1·40	13	–	–	
3·0 m	0·21	14	0·47	13	0·80	22	0·56	34	0·62	8	
XS 7											Run
1·0 m	1·17	18	0·87	23	1·44	12	1·44	12	0·50	4	
2·5 m	0·37	11	0·31	16	0·69	22	0·43	42	0·24	12	
3·0 m	0·80	9	0·85	12	0·66	20	0·43	54	0·12	17	
3·5 m	0·79	14	0·98	14	1·36	15	1·33	17	0·69	13	
XS 8											Run
0·5 m	0·85	9	1·12	11	1·31	12	1·35	16	0·29	7	
1·0 m	0·38	16	0·45	16	0·93	15	1·03	16	0·42	10	
2·0 m	0·25	12	0·41	20	0·55	13	0·50	22	–	–	
2·5 m	0·19	16	0·20	15	0·70	11	0·28	32	–	–	
3·0 m	0·94	11	1·01	9	1·43	13	1·08	17	0·48	8	
3·5 m	1·27	16	1·31	11	0·76	16	1·31	14	0·78	8	
XS 9											At step
1·0 m	1·02	10	0·57	14	0·64	36	0·13	92	0·98	31	
2·0 m	0·89	7	0·74	7	0·99	19	1·34	16	0·89	10	
2·5 m	0·78	10	0·65	12	−0·03	300	0·66	29	0·58	10	
3·0 m	0·20	10	0·34	18	0·53	53	1·47	25	0·06	17	
XS 10											Upstream from step
1·0 m	−0·12	67	−0·08	38	0·04	275	−0·04	100	−0·01	300	
1·5 m	0·13	46	0·16	56	0·56	130	0·51	110	0·50	18	
2·0 m	0·45	20	0·42	21	0·66	23	0·47	40	0·30	10	
2·5 m	0·70	16	0·50	12	0·93	26	0·97	26	–	–	
3·0 m	0·80	24	1·04	23	0·16	94	1·99	51	−0·04	100	
3·5 m	0·74	16	0·88	16	1·23	24	1·21	25	–	–	
XS 11											Downstream from step
1·0 m	0·05	80	−0·07	43	0·72	40	0·26	62	0·06	83	
1·5 m	0·002	70	0·34	44	0·94	39	0·15	187	0·20	75	
2·0 m	−0·03	833	0·11	182	0·38	55	–	–	0·13	308	
3·0 m	0·49	51	0·85	54	−0·05	1080	0·78	69	0·12	50	
3·5 m	0·03	33	0·38	32	0·18	44	1·06	38	–	–	

standard deviations expected with higher average velocities. A transformation using the reciprocal of the log base 10 of coefficient of variation (1/log CV) data was performed to produce a normal distribution for the coefficient of variation dataset before the ANOVA tests were performed. Except where noted, a significance level of 95 per cent ($\alpha = 0{\cdot}05$) was used for all analyses.

Bedforms were categorized as one of four types: upstream from step (0·5 m upstream from the step lip); at step (on the step lip); downstream from step (0·5 m downstream from the base of the step riser); and run (in a lower gradient reach of more uniform grain size) (Table I). To determine whether average velocity differed in the four different bedform locations, a one-way ANOVA test between average velocity and bedform type was performed. Because we suspect that variations in reach characteristics and discharge level are masking differences in average velocity response between bedforms, ANCOVA tests were conducted using bedform type and reach gradient or depth to predict average velocities. The ANCOVA tests use variations in either reach gradient or depth as a regression effect and then test for significant relations between bedform type and average velocity. Reach gradient is selected as the most appropriate regression effect to account for variations in reach characteristics based on the relatively high correlation observed between average velocity and reach gradient. Depth is selected to represent the expected increase in average velocity with higher discharges and stages.

An ANOVA procedure was also conducted between bedform type and the coefficient of variation (1/log CV) data to test whether the level of velocity fluctuations varied by bedform type. Based on the resulting significant relation between bedform type and the coefficient of variation data, a Tukey–Kramer HSD comparisons of means test was performed to determine which coefficient of variance (1/log CV) means are statistically different from each other. The Tukey–Kramer HSD method is a statistically robust and conservative test that identifies statistical differences in mean values of three or more groups of categorical data (Ott, 1993). The results of the analysis show which bedforms have statistically different mean values from other bedforms based on the assumption of equal variances among categories.

RESULTS

Figure 2 illustrates velocity characteristics at each of the measurement cross-sections during low and high discharges. As discharge increases, the magnitude of velocity fluctuations increases at each of the cross-sections, with the largest increases downstream from a step. Mean velocity increases with discharge upstream from a step, decreases at the step and downstream from the step, and increases or decreases in a run. The decrease in mean velocity at steps and downstream from steps is partly driven by more frequent and larger negative velocity readings at these sites as discharge increases. Velocity data are summarized in Table II.

Characteristics of velocity profiles

A total of 24 velocity profiles were plotted both as mean velocity versus ln depth, and as velocity coefficient of variation versus ln depth (elevation above the channel bed) (Figure 3). The eight velocity profile locations were subdivided in three different manners. The first subdivision, based on bedform type, produced four groups: upstream from step (cross-section (xs) 2, xs 10), at step (xs 1, xs 9), downstream from step (xs 3, xs 11), and run (xs 7, xs 8). The second subdivision, based on bed roughness, produced three groups: high k value ($3{\cdot}5D_{84}$ of 450–550 mm), moderate k value (250–350 mm), and low k value (150–200 mm). The third subdivision, based on reach gradient, also produced three groups: steep gradient (0·1232), moderate gradient (0·0625), and low gradient (0·0254).

Visual analyses of velocity profiles suggest that subdividing the profiles on the basis of bedform type produces the most consistent or similar groupings. Of course, bedform type, bed roughness and approach gradient are not independent of one another. Within the bedform grouping, it is also possible to perform some groupings based on similarities and differences in the shape of the velocity profiles and trend in coefficient of velocity magnitudes. The resulting groupings suggest that run and step locations are similar in some velocity characteristics, but are fundamentally different from areas above and below steps.

In general, the locations above steps display the most sporadic velocity profiles, with a non-uniform increase in velocity towards the top of the profile, low to high velocity gradients (as judged by the rate of

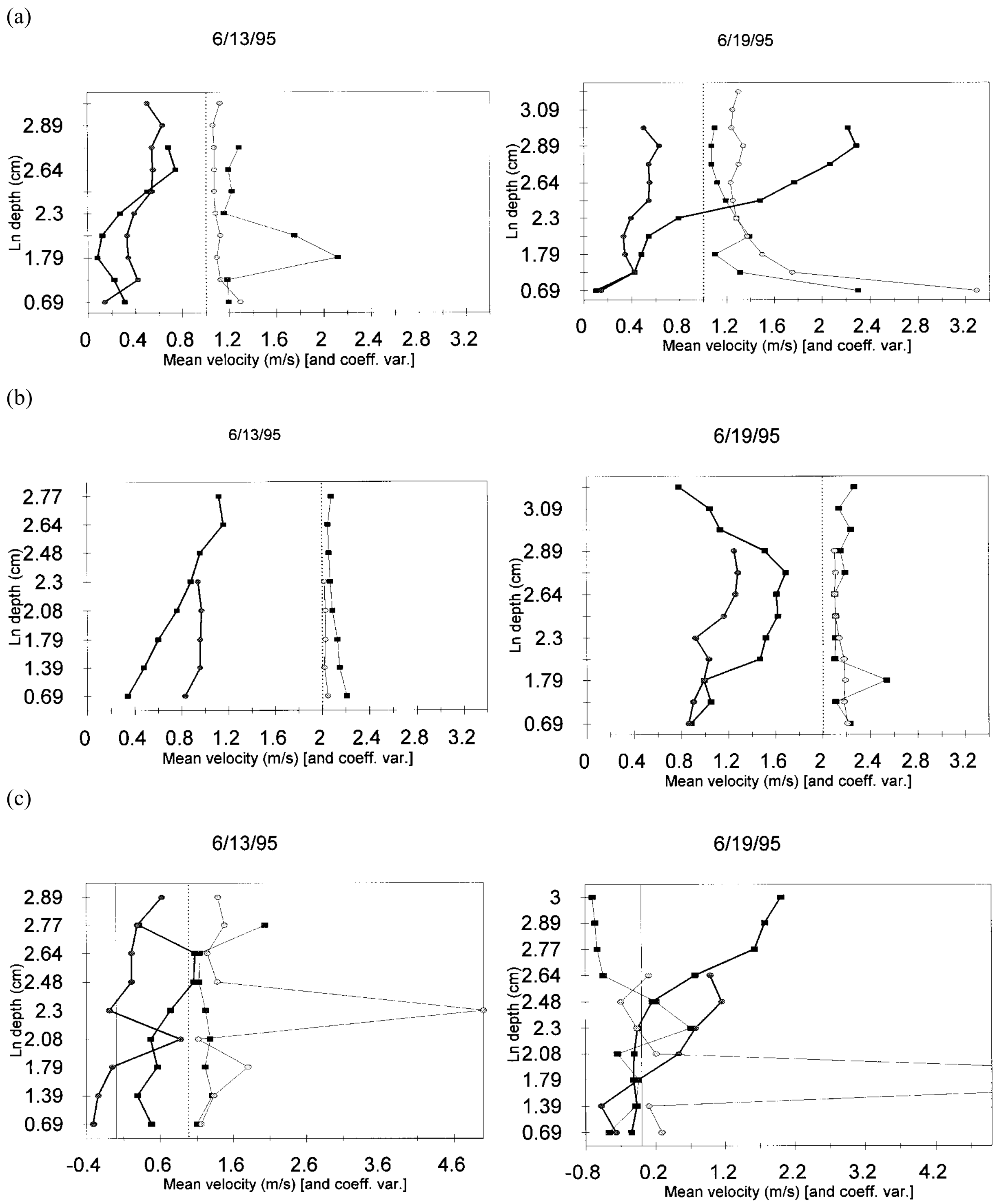

Figure 3. Velocity profiles for the two cross-sections at each bedform type, grouped by bedform, for 13 June (low discharge) and 19 June (high discharge) 1995. Mean velocity versus ln depth is shown by the profiles with heavy lines. Coefficient of variation of velocity versus ln depth is shown by the profiles with lighter lines. These latter plots, although to scale, do not correspond to the values on the x-axis. The y-axis for these plots is the vertical dotted line (a) Cross-sections upstream from step; (b) cross-sections at step; (c) cross-sections downstream from step. The y-axis for the 19 June mean velocity and velocity coefficient of variation profiles is the same. One point in a coefficient of variation profile is off the scale (the point would be at a value of 11 on the mean velocity x-axis). (d) Cross-sections at run

(d)

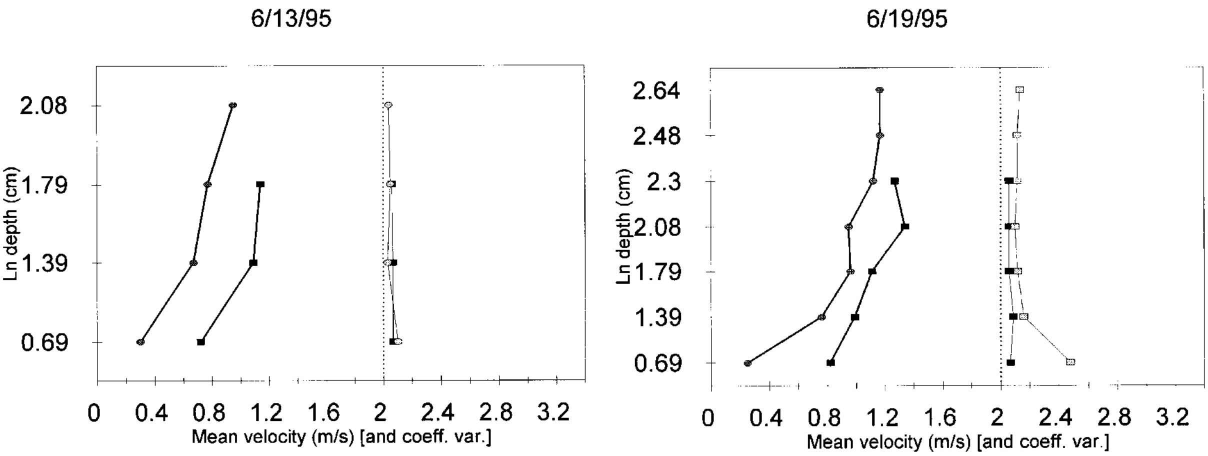

Figure 3 (Continued).

velocity increase for the three measurement points closest to the bed), and high near-bed coefficients of variation (Figure 3a). Like the step and run locations, velocity fluctuations tend to be highest near the bed, but are generally much higher than in the other two areas, especially as distance from the bed increases.

The locations at steps have profiles with a distinct zone of high velocity near the water surface, moderate to high velocity gradients, and low coefficients of variation (Figure 3b). The locations on runs have profiles with a steady increase in velocity towards the top of the profile, high velocity gradients, and very low coefficients of variation (Figure 3d). In both cases, the coefficient of variation decreases exponentially with distance from the bed and then levels off in the upper two-thirds of the profile. Even the highly non-logarithmic velocity profile at the step on 19 June has little influence on the level of velocity fluctuations higher in the flow.

Unlike the other three areas, locations below steps tend to exhibit a negative near-bed velocity zone and a high velocity zone near the water surface, low velocity gradients, and a distinct zone of high coefficients of variation near the profile mid-point (Figure 3c). The zones of high velocity fluctuation correspond closely to the depths separating downstream flow from reversed flow. In these areas, average velocities approach zero and coefficient of variation values achieve their highest level in any of the profiles. There is also little evidence for the decrease in the level of velocity fluctuations with increased distance from the bed, as clearly depicted in the other three channel locations.

Statistical analyses of velocity characteristics and potential control variables

The ANOVA analyses for average velocity show no significant differences in average velocities between the four bedform types. The resulting p-value for bedform type is 0·1303 with an R-square value of only 0·0312. Similarly, the ANCOVA analysis with reach gradient does not identify bedform type as a significant variable. Although reach gradient is significantly related to average velocity, with a p-value of 0·0021, the bedform variable has a p-value of only 0·5287 and the model fails the statistical test for lack-of-fit (Ott, 1993). Conversely, when the average velocity data are adjusted for variations in average velocity resulting from increases in stage (depth), bedform type is significantly related to average velocity, with a p-value of 0·0024. Within this analysis, the runs are significantly different from areas below steps at the 95 per cent confidence level (p-value = 0·0275), and significantly different from areas above steps at the 90 per cent confidence level (p-value = 0·0699). In both instances, runs have higher average velocities than the other two locations.

Unfortunately, the second ANCOVA also suffers from lack-of-fit problems, which suggests that the combined effect of the variables bedform type and depth does not explain a sufficiently high portion of the variability in average velocities to be significant. Therefore, these results should be viewed with care.

The analysis of the distribution of coefficient of variation of velocity values indicates that runs had a much narrower distribution, indicating lower variation in velocity fluctuations (CV). The coefficient of variation distribution for runs also fails the test for normality even after transformation into reciprocal of log values (1/log CV) because of a single outlier. The outlier was removed and bedform locations above steps, at steps, below steps and in runs were tested for unequal variance. The F-tests for unequal variance (SAS, 1994) confirm that runs have lower velocity variability (1/log CV) in addition to the lower coefficient of variation (CV) mean values than the other three locations in and around steps. Therefore, the F-test supports the notion that locations in runs are statistically different with respect to coefficient of variation from areas above steps, at steps and below steps, and it is not necessary to test run locations with ANOVA.

Based on the previous results, the subsequent ANOVA test on the influence of bedform type on velocity fluctuations (1/log CV) was only conducted for the three bedform locations associated with steps. The resulting ANOVA for bedforms above steps, at steps and below steps is significant, with a p-value of 0·0012. The Tukey–Kramer HSD comparisons of means test indicates that areas at steps are lower than both areas above steps and areas below steps. According to these analyses, there is no indication that areas below steps are significantly different from areas above steps.

DISCUSSION

Velocities and turbulence generation

There is insufficient statistical justification to document differences in average velocities for the various bedform features. Although runs appear to have higher average velocities than other locations, there is too much unexplained variability to be certain. An obvious conclusion is that these results indicate high variability in average velocity for any particular feature that would tend to mask differences between features. However, these results could indicate an equalization of velocities between features with increasing stage in the manner originally proposed by Keller (1971). In either case, it is difficult to make definitive conclusions based on the average velocity data.

We used the velocity profiles from East St Louis Creek to infer dominant mechanisms of turbulence generation at the measurement sites. Most turbulence is generated by the sharp velocity gradient and the associated vorticity near the bed of the channel (Nelson *et al.*, 1995; Clifford, 1996). Fluid interactions with the bed roughness create bursting flow phenomena and large turbulent fluctuations (Nelson *et al.*, 1995). For example, bed-generated velocity fluctuations dominate the coefficient of variation plots in runs (Figure 3d). The bed-generated turbulence also appears to dominate the locations above steps and slightly influences locations at the steps. However, an F-test for unequal variance of 1/log CV values indicates that velocity fluctuations in runs are statistically lower than values associated with steps. Despite the differences between runs and step locations, the general trend of increasing velocity fluctuations with depth is similar in both features but differs from locations above and below steps.

The different response in bed shear above steps versus at steps and in runs reflects differences in flow acceleration and deceleration. Pressure gradients are creating a self-enhancing effect on bed turbulence generation in areas above steps, and suppressing turbulence at the steps and in runs. The flow above steps is generally decelerating due to backwater effects created by the step. Under these adverse pressure gradient conditions, turbulence is amplified (Schlichting, 1968). Figure 3b shows a dramatic increase in near-bed velocity fluctuations in response to this influence. Conversely, flows over the step are accelerating and plunging into the downstream pool due to gravity forces. Similarly, the higher average velocities in runs suggest flow acceleration from areas below steps to the run. In runs and at steps, the accelerating flow and favourable pressure gradients tend to suppress turbulence generation (Schlichting, 1968). Consequently, the levels of velocity variation for run and step locations are lower than areas immediately above or below the step. These observations are supported by the lower coefficient of velocity mean values (CV) and the lower variance of run velocity fluctuations (1/log CV). Similarly, the ANOVA results for bedform type and coefficient of variation (1/log CV) show that areas at steps have lower levels of low-frequency velocity variation.

Turbulence is also generated when there is a wake with shearing flows (Tritton, 1988). The dramatic velocity gradient created with a change in direction of the flow over a short distance creates strong vorticity and turbulence (Tritton, 1988). In the velocity profiles, high coefficients of variation (CV) correspond closely to the depth of flow dividing primarily downstream and upstream flowing water (Figure 3a and b). In particular, the locations below steps appear to be primarily influenced by this type of wake turbulence from mid-profile shear layers. Large wakes or roller eddies are probably created where the flow from the steps plunges into the pools located below the steps (Chanson, 1996). The roller eddies form near the bed, or small wakes may form downstream from local bank projections into the flow. Flow reattachment would be expected on the pool exit-slope at the end of pool (Thompson *et al.*, 1998), downstream from our velocity measurement locations. In a manner similar to locations above steps, the flows below steps also decelerate along the downstream end of the pool, creating an adverse pressure gradient and enhanced turbulence generation. The existence of the adverse pressure gradient in these locations becomes intuitive with the recognition that the recirculating flow in the wake or roller eddies must have a force driving flows in the upstream direction and a downstream reattachment point. The importance of wake turbulence is further demonstrated by the near-bed velocity gradients below steps. The near-bed velocities are relatively low in comparison to run and at step locations, which should indicate low turbulence generation from the bed. However, the statistical results confirm that velocity fluctuations below pools are higher than either in runs or at steps. The shear layers, positioned higher in the water column, are supplying the turbulence and resulting velocity fluctuations in these areas.

The statistical results also suggest that areas below steps have some overlap in characteristics with areas above steps. In this case, the similarity of pressure gradients may explain the lack of a significant difference. The lesson may be that a simple time series of velocity measurements may not distinguish fundamental differences in morphologic flow characteristics. Within this context, it is important to recognize the relative importance of the dominant pressure gradient and the local mechanisms for turbulence generation.

Implications for flow resistance

It is also useful to consider form drag versus skin friction. Form drag results primarily from the development of wakes. Whittaker and Jaeggi (1982) have hypothesized that step–pool bedforms effectively maximize energy expenditure by increasing form resistance. The large velocity fluctuations below steps are the physical representation of this energy expenditure. Conversely, runs have minimal form drag and dissipate most energy with skin friction and in small wakes behind individual roughness elements. The high near-bed velocity gradients in runs and above steps highlight the influence of skin friction. Because the overall energy expenditure is much lower in this case, the velocity fluctuations are generally lower in runs than in locations associated with steps.

It has also been widely accepted that bedforms are created at high flow (Keller, 1971; Whittaker and Jaeggi, 1982; Clifford, 1993a). Because bed-generated turbulence will tend to have a decreased importance as stage increases (Jarrett, 1984), and wake-generated turbulence should increase as the velocity difference between shearing flows increases (Tritton, 1988), it follows that wake-generated turbulence will tend to be progressively more important as discharge increases. Although the statistical tests for average velocity were inconclusive, the higher average velocities in runs support the assertion that bed-generated turbulence and skin friction are less effective energy dissipators than wake-generated turbulence and form drag. Because the wake-generated velocity fluctuations were highest below steps, this might suggest that the formation of bedforms at high flow creates a more effective turbulence-generating mechanism than skin friction alone, and may maximize energy expenditure along a reach. Analysed in a slightly different manner, the existence of adverse pressure gradients above and below the steps indicates resistance to flow. These adverse pressure gradients are in response to the downstream form drag created by steps and pool exit-slopes, and appear to strongly influence both bed and wake turbulence generation.

Our interpretations of the velocity data from East St Louis Creek support earlier work of other investigators on pool–riffle sequences and channel beds of varying roughness. Several investigators have described the presence of a near-bed zone dominated by obstacle-derived vortices in channels with poorly sorted gravels (Kirkbride, 1993; Robert *et al.*, 1993; Ferguson *et al.*, 1996; Roy *et al.*, 1996). The presence of protuberant

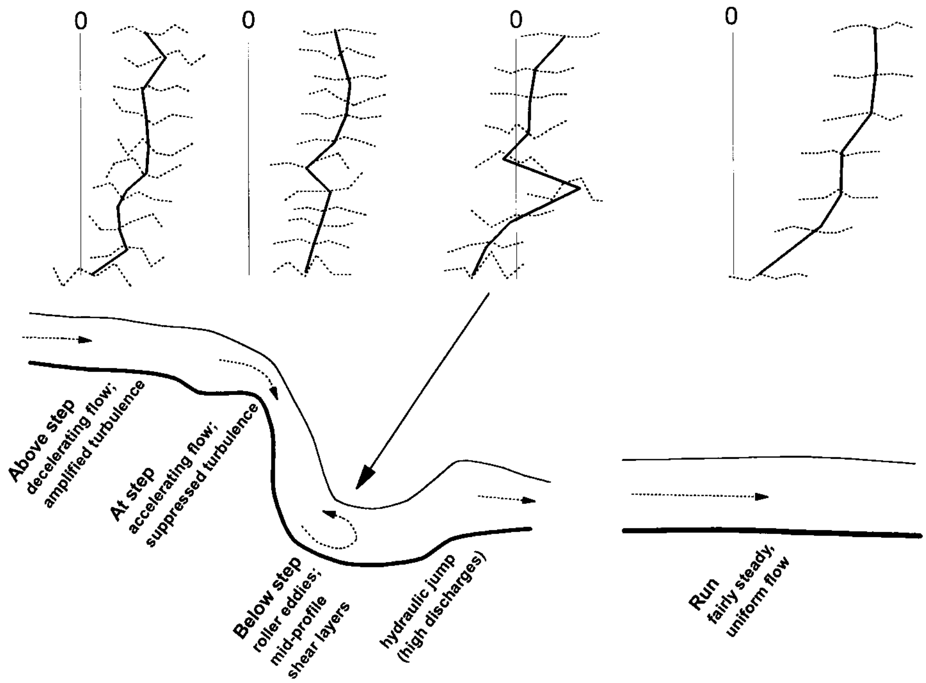

Figure 4. Schematic illustration of the flow characteristics along a step–pool sequence and a run. The upper figures are vertical velocity profiles (velocity on the x-axis, flow depth on the y-axis) in the channel thalweg, with vertical axis of 0 m s^{-1}. The dotted horizontal lines are velocity time series and represent the magnitude of velocity fluctuations (time on the x-axis, velocity on the y-axis) through a 1 min interval at each measurement point on the velocity profile; all lines are plotted to the same scale. The lower portion of the figure illustrates the dominant flow characteristics at each measurement cross-section

clasts increases turbulence intensity and appears to dominate turbulence generation in this situation (Robert *et al.*, 1996). These results apply to the run and upstream from step cross-sections along East St Louis Creek. In the runs, which have more well-sorted beds, higher frequency variations in velocity (as judged by coefficient of variation for velocity) were relatively low and decreased with height above the bed. As bed roughness from protuberant clasts increased, in the sites upstream from steps, velocity variability also increased.

A second discrete scale of bed roughness may occur with the presence of bedforms (Clifford *et al.*, 1992). Flume experiments on the generation of wake vortices suggest that bedforms with larger-than-average wavelengths or heights contribute most of the variation in flow resistance in this case (Nordin and Algert, 1966). This is readily observable along the step–pool reaches at East St Louis Creek, which have a higher turbulence intensity than the reaches of uniform bed gradient (the run of cross-sections 7 and 8). Higher frequency velocity variations, as indicated by the coefficient of variation for velocity, are particularly large immediately downstream from a bed-step, and may be caused by roller eddies associated with the bed step.

The differing flow structures and associated higher frequency velocity variations are schematically illustrated in Figure 4. The sample velocity profiles and velocity time series in this figure illustrate the larger high-frequency velocity variations and mid-profile shear layers associated with step–pool bedforms.

CONCLUSIONS

Working in a braid-bar reach of a small gravel-bed river, Clifford (1996) found systematic associations between velocity variation and individual grains, bed microtopography, channel bedforms and channel

planform. These associations are also influenced by changes in flow stage and by the height at which measurements are made in the boundary layer. Similarly, our characterization of velocity fluctuations along a small mountain channel with step–pool bedforms suggests that these fluctuations correlate to some degree with both discharge and channel characteristics. As might be expected, flow tends to become more variable as stage increases, with the best correlations occurring at low-gradient reaches with fairly constant bed roughness. Velocity profiles suggest that locations downstream from bed-steps are dominated by wake turbulence from mid-profile shear layers. Locations upstream from steps, at steps and in runs are dominated by bed-generated turbulence. Adverse pressure gradients above and below steps may be enhancing turbulence generation, whereas favourable pressure gradients at steps are suppressing turbulence. The wake-generated turbulence leads to higher energy dissipation in step–pool reaches relative to more uniform-gradient reaches.

Results from this study are similar to those of previous studies that demonstrated varying scales of turbulence and flow structure associated with varying bedforms and bed roughness along pool–riffle sequences. The bed-generated turbulence that predominates at step lips and upstream from steps, and in runs, is analogous to the turbulence that dominates riffles and runs in pool–riffle channels. The wake-generated turbulence in step–pools is also analogous to the shear associated with lateral eddies in larger pools, except that in step–pools the shearing occurs primarily at mid-profile and across the channel rather than throughout the profile and along the channel margins. In both types of channel, spatial differences in turbulence presumably both reflect bed topography, and control bed topography by influencing sediment movement.

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